Frequency Comparisons via GPS Carrier-phase:

Jump Processing, Temperature Compensation and Zero/Short-baseline Noise-floors

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Motivations and Challenges behind using GPS carrier-phase receivers for frequency transfer

- Motivations:
  - Operational environments: space, deep-space network, field-work
  - Long-term monitoring
- Challenges:
  - Piecing data together into continuous sets
  - Day boundary and batch boundary jumps
  - Receiver resets/Losing satellites (data gaps and jumps)
  - Sensitivity to temperature
  - Antennae and cabling (Not addressed here. We used high quality ones.)

Outline

- 5-Stage Processing Algorithm
- Measurements
  - Ideal environment: zero-baseline, common-LO, temperature stable
  - Temperature impact, calibration and compensation
  - Reproducibility and receiver comparison
  - Zero vs. short baseline
  - Long baseline implications
- Conclusions

Background/Definitions:
GIPSY, x(t), y(t), Single Receiver vs. Pair Data

- First we process with "GIPSY" [actually, GIPSY-OASIS: GPS-Inferred Positioning System and Orbit Analysis Simulation Software].
  - gives offset/delay x(t) between the receiver clock and either a remote or local reference clock
  - y(t) throughout talk is fractional frequency (point by point derivative of x(t))
- We present *mostly* receiver pair data, but first describe single receiver data.

Single Receiver Data: receiver-under-test's delay, x(t), relative to a reference clock/receiver

- How we calculate it:
  - use GIPSY in single receiver daily static Precise Point Positioning (PPP) mode
  - determine receiver's position once a day (using the ionosphere-free pseudo-range and carrier-phase observables -- PC and LC)
  - use JPL's GPS orbit and clock products (GPS satellite transmitter clocks determined relative to ground reference receiver)
  - reference clock chosen each day from list of clocks steered to UTC (usually a USNO receiver)
    - (All GIPSY users get the same reference clock.)

Background/Definitions:
GIPSY, x(t), y(t), Single Receiver vs. Pair Data

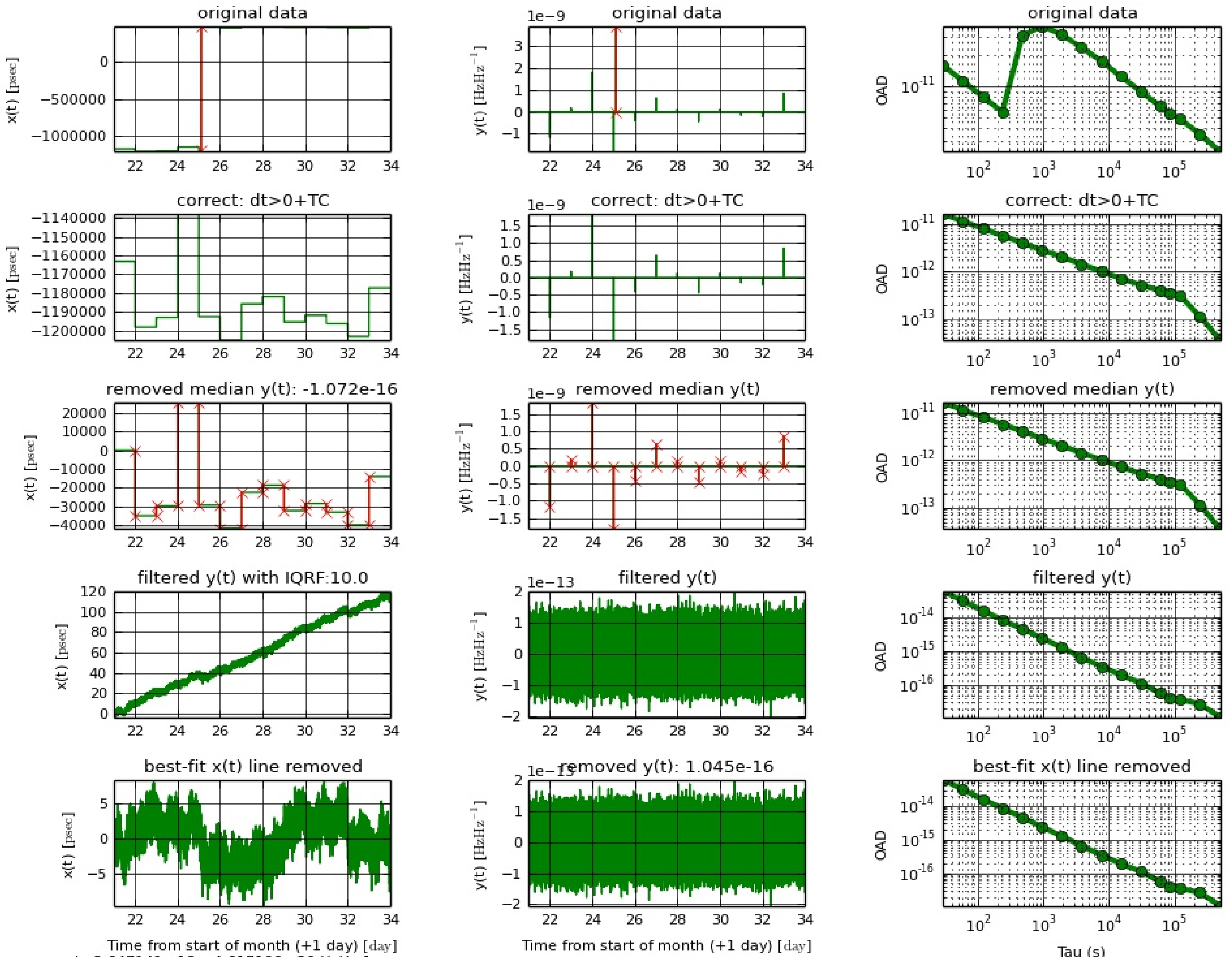
Receiver Pair Data: relative delay x(t) between two receivers under test (for zero/short-baseline)

- How we calculate it:
  - derive it directly from GIPSY by assigning one receiver to be the reference
  - fix GPS satellite orbits (from JPL's GPS orbit and clock products), but solve for 1) transmitter clocks and 2) ground-based receiver that is NOT the reference

- Removes common-mode troposphere and ionosphere delay along each transmitter-receiver line of sight (gets absorbed into the estimated transmitter clock).
- x(t) may include fixed internal delays in the receivers-under-test (ok because we're using for relative frequency measurements)
- Can use a single carrier-phase frequency such as L1 instead of the LC/PC ionospheric-free combination (since the frequency-dependent ionospheric delay is accounted for in the estimated transmitter clocks). This further reduces noise.

5 Stage Processing Algorithm (all corrections are applied to x(t))

1. Gather x(t) data between START and STOP times.
2. Correct jumps associated with data gaps (use median y(t)).
3. Remove slope (use median y(t)); flag points for stage-4 y(t)-filtering
4. Correct jumps at flags (base decision on iqr which describes typical scatter)
5. Remove another slope (linear best fit y(t) now)



Allan deviation calculations for data with gaps

- Problem:
  - Allan deviation expects x(t) data equally spaced in time. Data gaps violate this.
- Solution:
  - Pad x(t) data with “bookkeeping” data in gaps to get back equally spaced x(t) data, solely as a placeholder for Allan deviation calculation. (Never used in rest of algorithm.)
- Details:
  - All $x(t-\tau)+x(t+\tau) - 2*x(t)$ second difference terms computed.
  - Some have real data, some placeholder.
  - Only those with real data are summed to calculate the Allan deviation.
- End result for Allan deviation:
  - represents true noise character during the times that we have data
  - does not reflect all events that happened during the timespan (because no information available during data gaps)

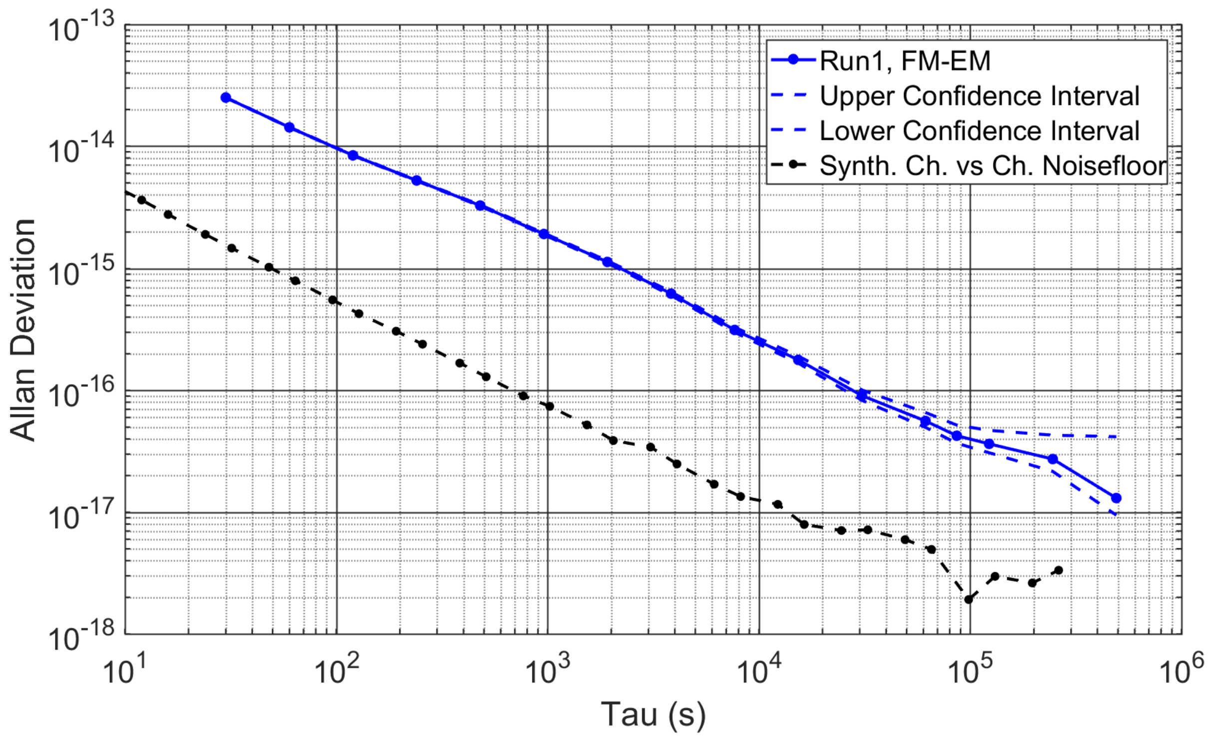
Measurements: Receivers Tested

Receiver Label	Receiver Type/Model	Location
JPLT	Ashtech Z12T	JPL FSTL
EM	DSAC Engineering Model	JPL (varied)
FM	DSAC Flight Model	JPL (varied)

- EM and FM built for DSAC (Deep Space Atomic Clock).

  - moved between different buildings at JPL during DSAC ground testing
  - on a thermally controlled plate when needed
- JPLT remained in our thermally controlled laboratory (Frequency Standards Test Lab -- FSTL).
- Measurements shown are noise floors taken before, in between, or after DSAC clock characterization campaigns.

Ideal-environment noise-floor: zero-baseline, common LO, common antenna

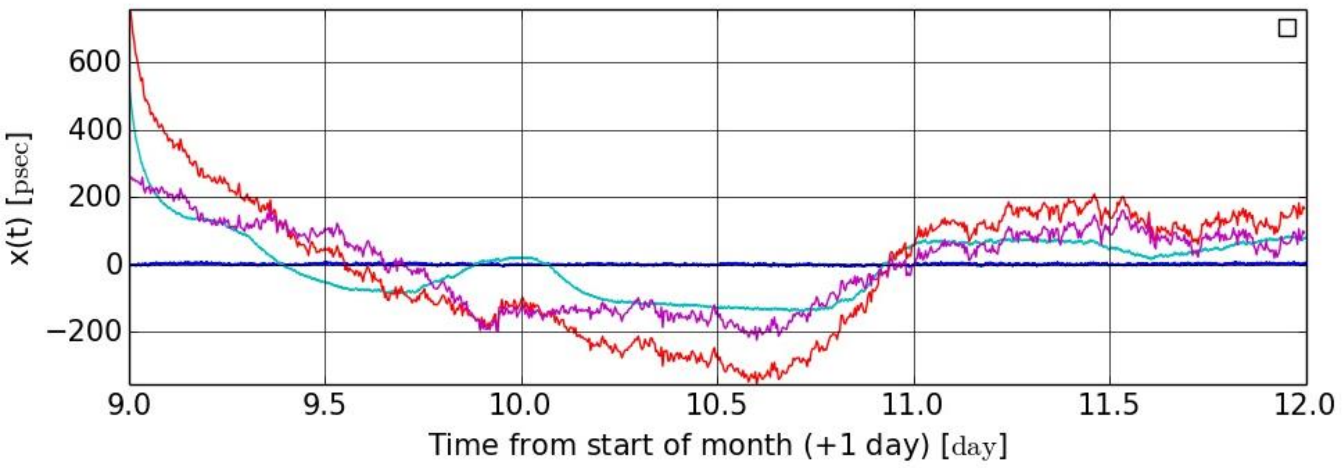


- FM-EM comparison:
  - Both in thermally controlled FSTL
- LO:
  - H-maser feeding 20.456 MHz (4-channel) synthesizer. One channel went to each receiver.

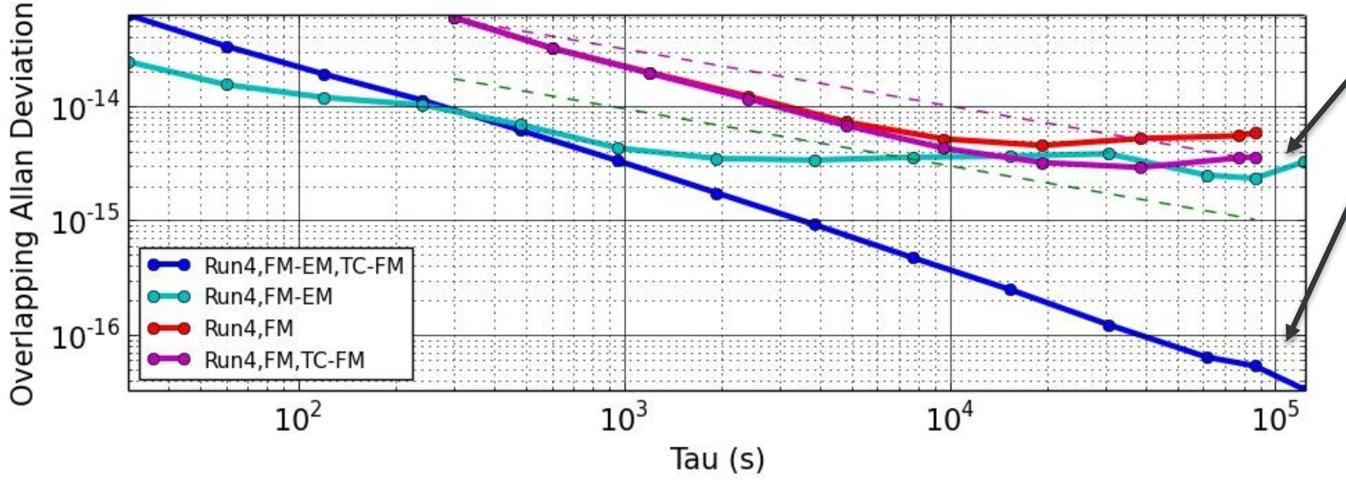
Allan Deviation:

- Below 10^{-16} at a day
- Down to $1x10^{-17}$ at $5x10^{5}$ s, with $4x10^{-17}$ upper confidence interval (1-sigma; assumes white noise).

Temperature Impact and Compensation



- FM-EM zero-baseline noise-floor again:
  - Both in Bldg 1 at JPL.
  - EM on thermal plate.
  - FM had thermal changes from warmup as well as room temperature, 5C in this case.

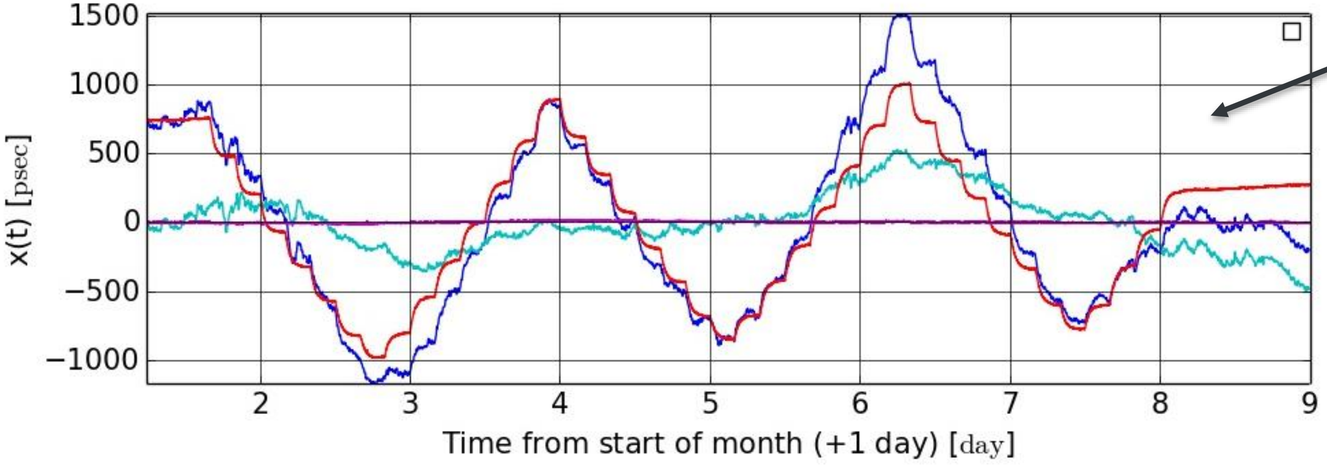


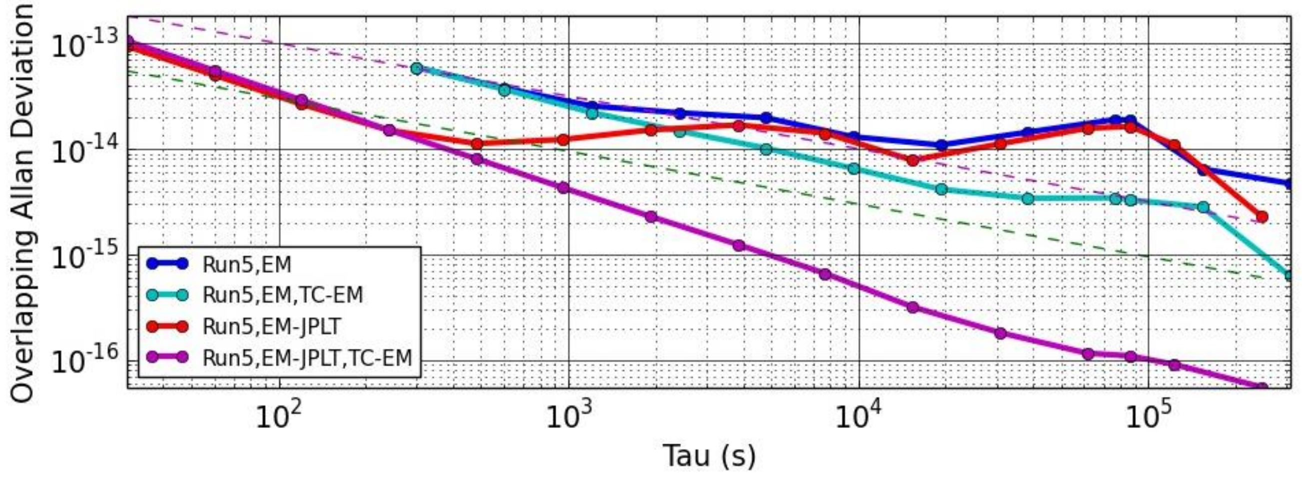
FM-EM, no temperature compensation

FM-EM, yes temperature compensation

Temp. correction brings Allan deviation down to expected level. (Small impact seen on single receiver data as well.)

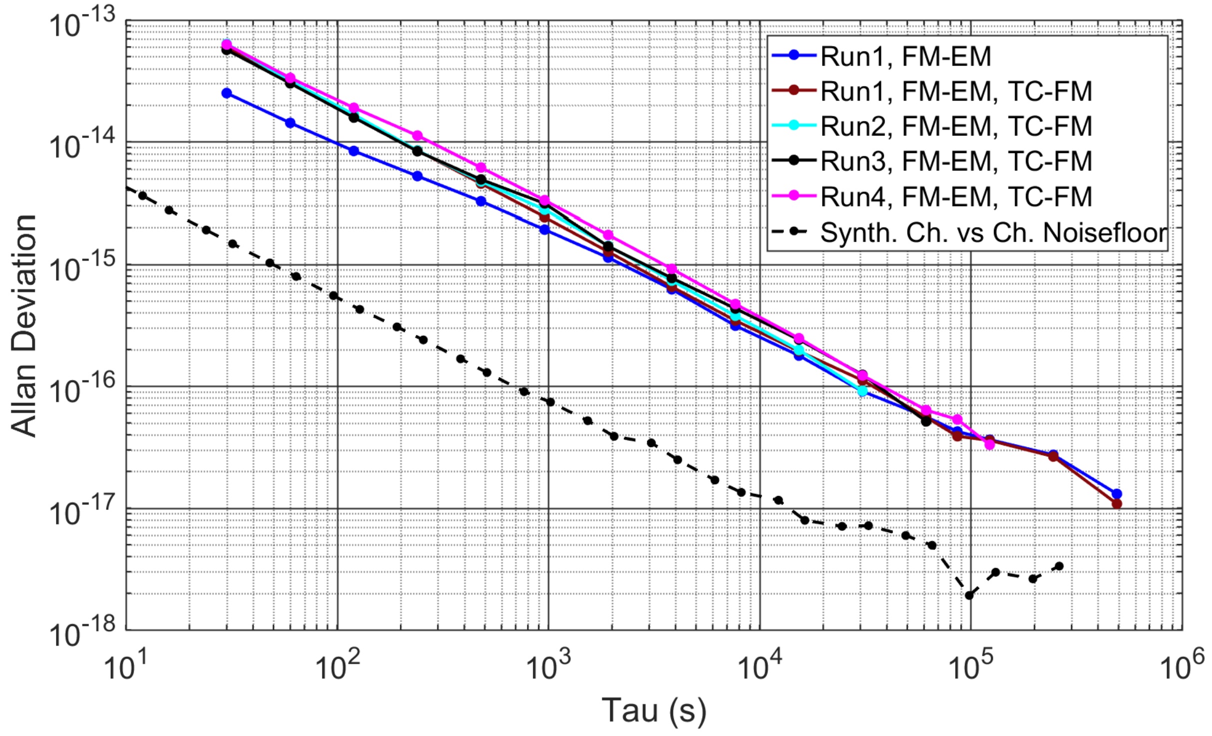
Temperature Calibration and Compensation





- Example Temp. Calibration (EM):
  - 45°C changes over several days
  - Measure receiver temperature (T) internally
  - Fit x(t) to a quartic polynomial in T(t).
  - Coefficients become the calibration coefficients
- Stability of Coefficients:
  - 2 FM calibration runs, 1 year apart, gave similar coefficients.
- Temperature Compensation: determine temperature-dependent delay at every epoch; subtract this from the originally determined x(t)

Reproducibility: FM-EM Noise Floors

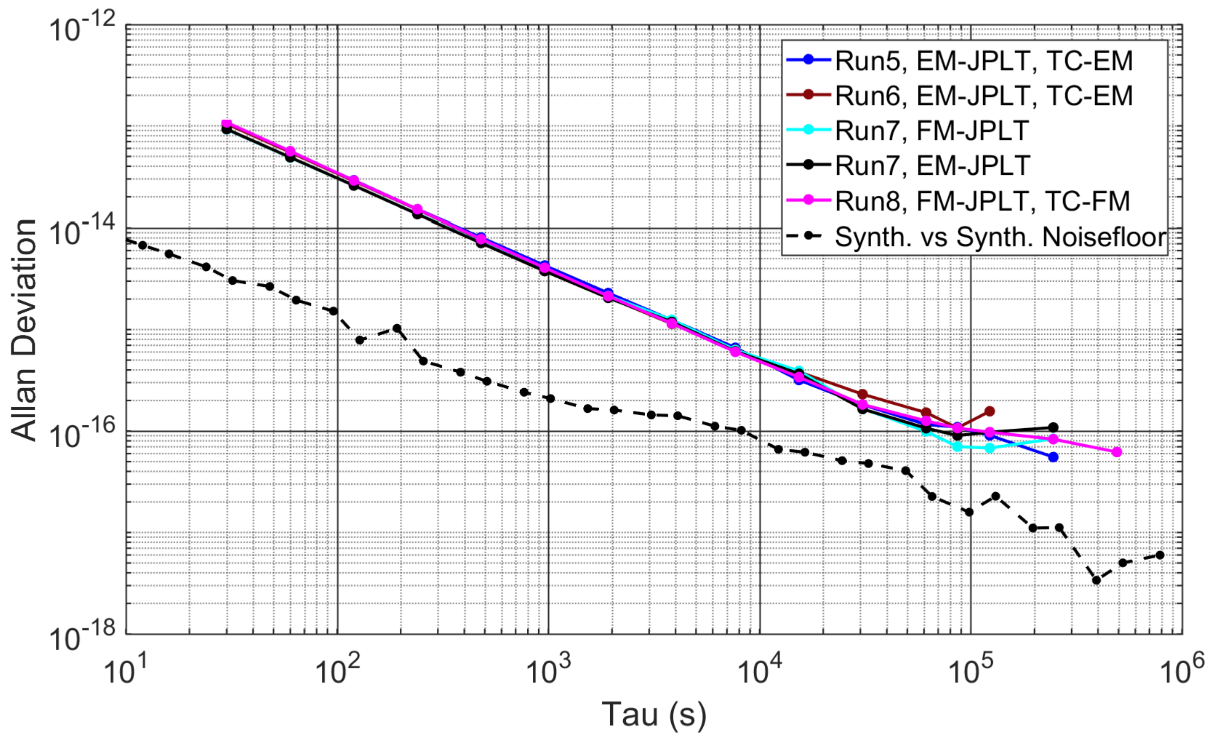


Dataset	Date Range (GPS Time)	EM/FM Location
Run1	12/21/2016 00:00 - 01/02/2017 23:59	FSTL
Run2	11/08/2015 00:00 - 11/08/2015 23:59	Bldg. 2, JPL
Run3	11/14/2015 00:00 - 11/15/2015 23:59	Bldg. 2, JPL
Run4	01/09/2015 00:00 - 01/11/2015 23:59	Bldg. 1, JPL

- Co-located receivers
- Different setups in different buildings, over 2 years, with and without temp. compensation.

Gives a feel for the reproducibility, and validates jump/temp. correction.

Reproducibility: FM-JPLT (and EM-JPLT) Noise Floors

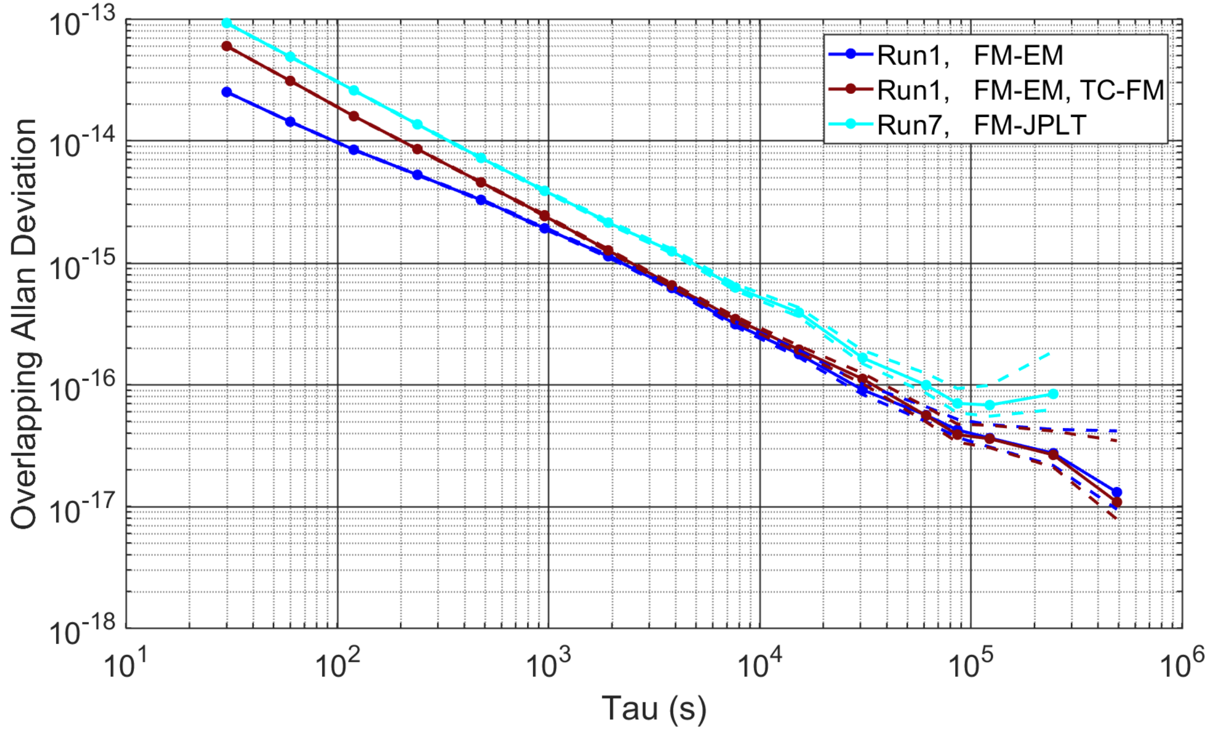


Dataset	DATE RANGE (GPS TIME)	EM/FM Location
Run5	03/01/2017 05:50 - 03/08/2017 23:59	FSTL (EM in thermal chamber)
Run6	12/20/2014 02:00 - 12/22/2014 22:00	FSTL
Run7*	12/21/2016 00:00 - 12/28/2016 23:59	FSTL
Run8	11/23/2016 00:00 - 12/13/2016 23:59	FSTL

- Co-located receivers in FSTL.
- Different setups, over 2+ years, with/without temp. compensation.

Same validation as FM-EM data, plus: FM-JPLT results agree with EM-JPLT.

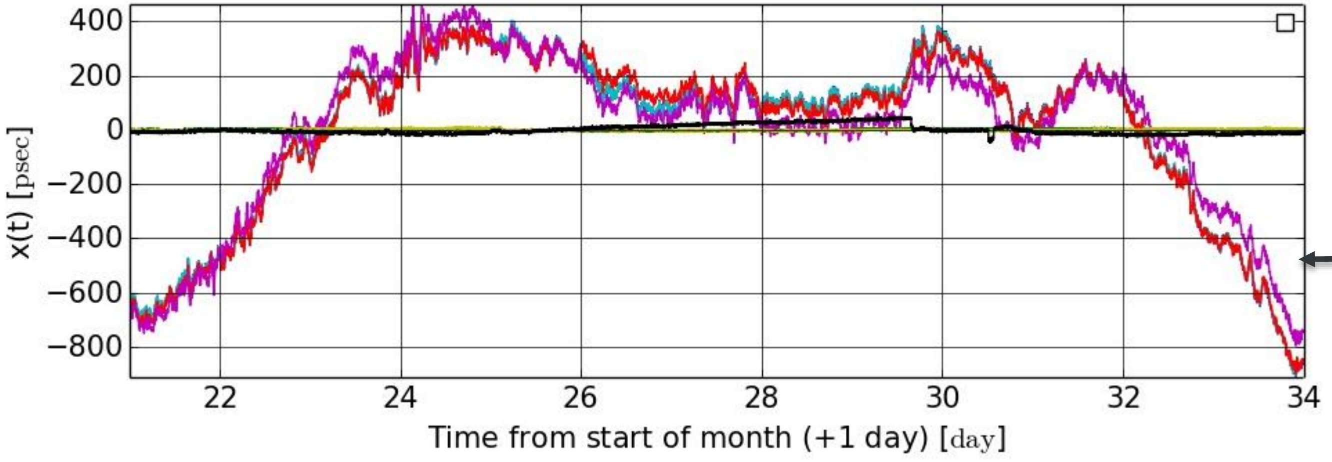
Comparison of Receiver Pair Noise Floors



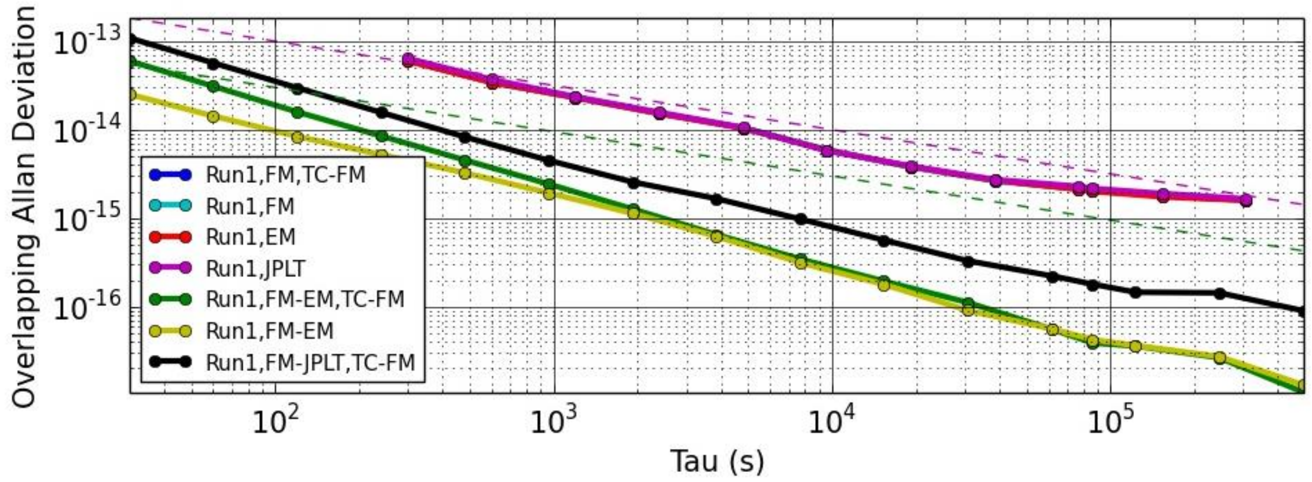
- FM-EM slightly better than FM-JPLT (EM-JPLT)

FM and EM have slightly better measurement noise than JPLT

Run1 Data: FM-EM, FM-JPLT, Single Receiver (Just EM or FM)



Single Receiver has GPS time transfer noise

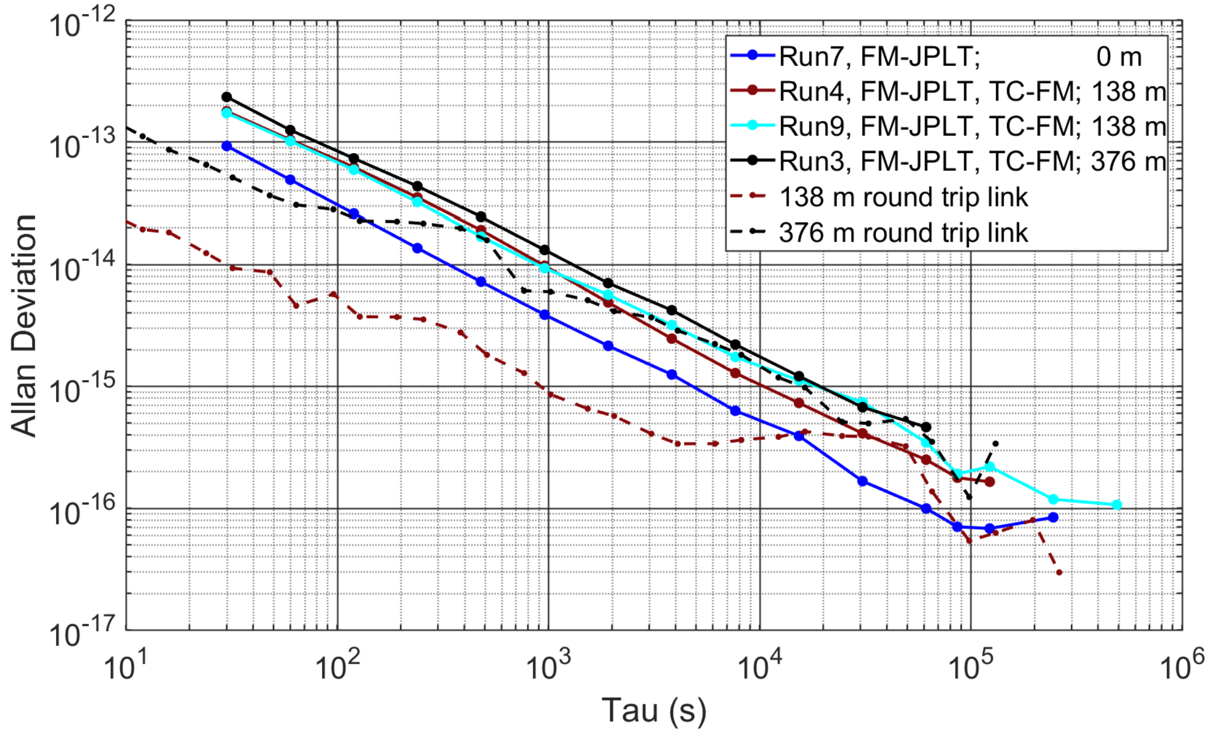


Single Receiver

FM-JPLT a bit worse than other FM-JPLT curves due to glitch visible above

FM-EM

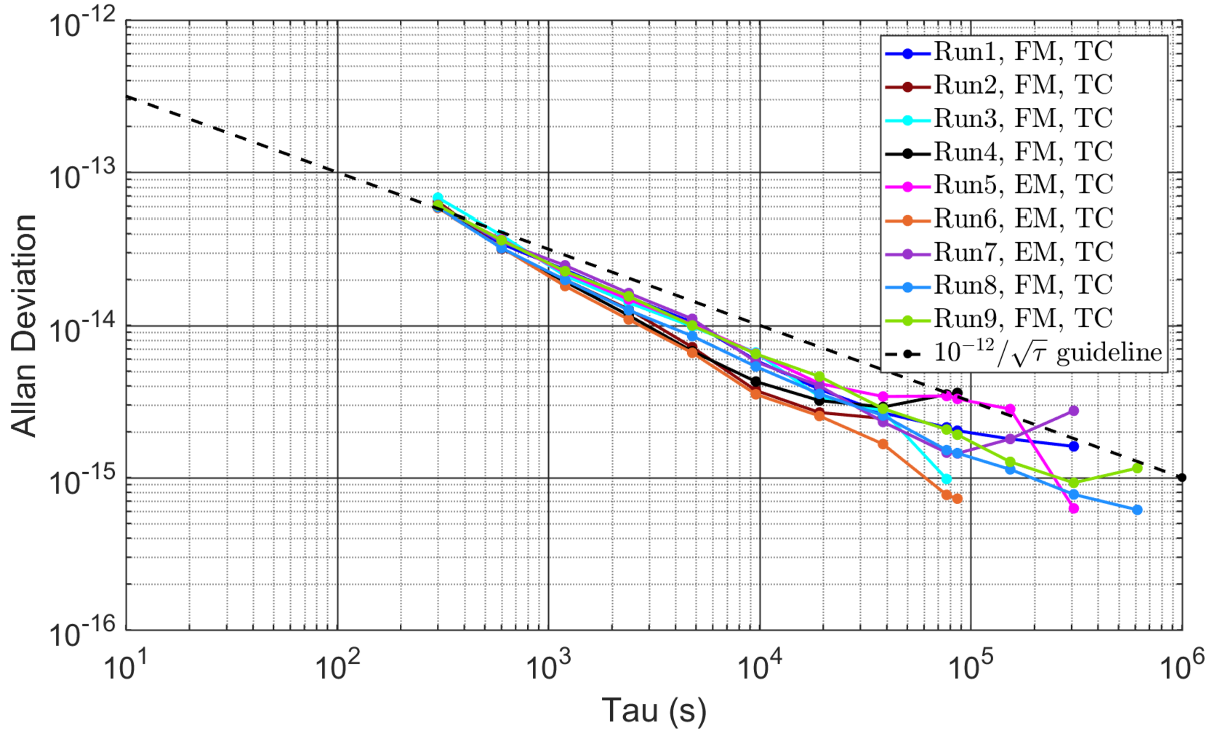
Short vs. Zero Baselines



- FM-JPLT short-baselines:
  - JPLT in FSTL
  - FM in another building (138m or 376m away).
  - H-maser was linked to these building via standard telecom fiber.
  - Link noise may be contributing to short baselines at some tau.

Short baselines a bit degraded from zero baselines, but still useful for clock comparisons in buildings that do not have stable references.

Single Receiver (Long Baseline) Allan Deviations



- Single receiver examples from all the runs shown.
  - with impact now from GPS time transfer and possibly from LO drift
- All fall below the $10^{-12}/\sqrt{\tau}$ guideline (at 1 day), which is what DSAC used for planning.

Direct validation (for DSAC) that the jump and temperature correction aren't leaving artifacts on single receiver data at the $10^{-12}/\sqrt{\tau}$ level.

Outline → Conclusion

- 5-Stage Processing Algorithm - explained
- Measurements
  - Ideal environment: zero-baseline, common-LO, temperature stable:
    1×10^{-17} at 5×10^{5} s (upper confidence interval = 4×10^{-17})
  - Temperature impact, calibration and compensation: shown & explained
  - Reproducibility and receiver comparison: overlaid curves validate algorithm and temperature correction to the level shown here; EM and FM flight receivers slightly better than Ashtech
  - Zero vs. short baseline: short baseline has slightly worse Allan deviation, but still useful for many clock comparison needs
  - Long baseline: algorithm validated for single receiver curves at the $10^{-12}/\sqrt{\tau}$ level, out to a day. (what was needed for DSAC)

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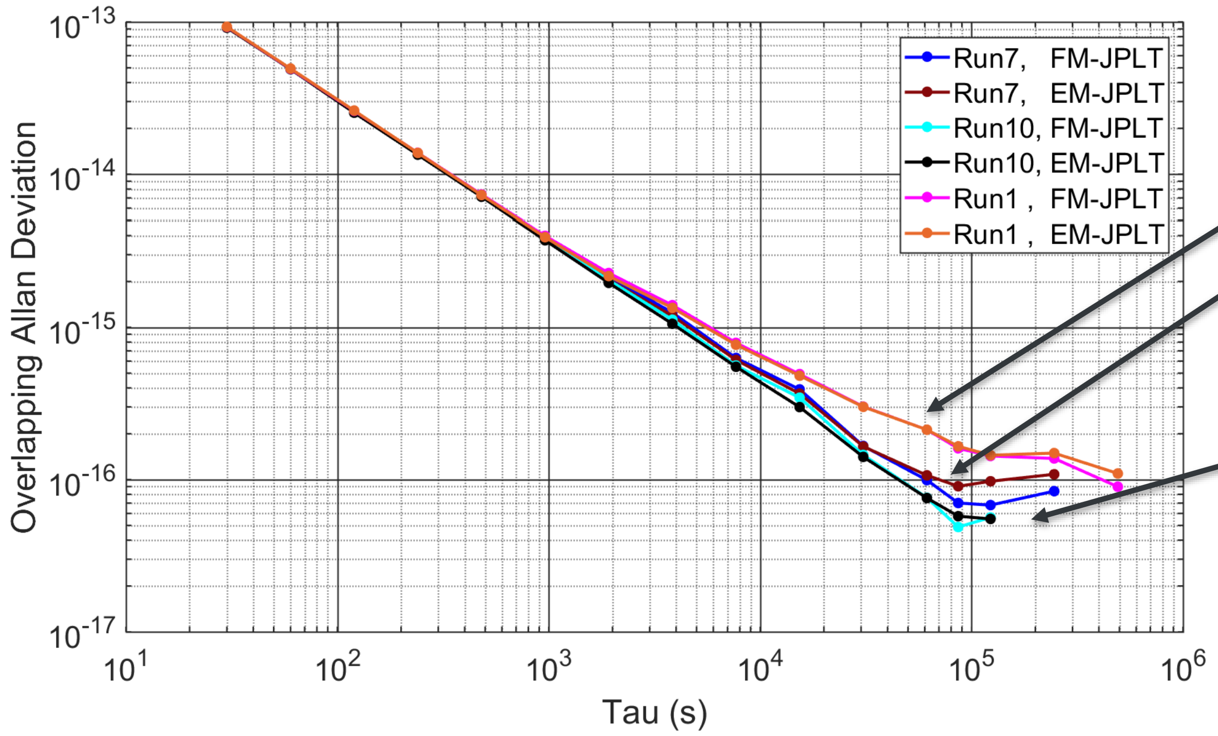
Backup Slides

Allan deviations for Run1's FM-JPLT match others when shortening the time period to avoid the obvious glitches



Degraded curves due to the x(t) glitch shown for Run1

Run7: baseline for the other FM-JPLT/EM-JPLT curves

4-day subset of Run1 chosen to eliminate all visible glitches

However, Run1's FM-EM curve matched other zero-baselines, even for this time periods with FM-JPLT/EM-JPLT glitches.

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